Rural Water Supply Pipelines and Water Quality Modeling

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Today’s Presentation

1. Introduction to Rural Water Supply Pipelines; Design and Construction
2. Studies in Deteriorating Water Quality
3. Water Quality Modeling – General
4. EPANET (Software) Application
5. Maintenance and Water Quality
6. Some Things That We Can Do Now
7. Concluding Remarks and Questions
Goals

- To give you some background in the design, construction and operation of rural pipelines with the hope that it assists you with water quality monitoring / management.

- To clearly demonstrate the need to understand not only the water quality aspects, but the hydraulic aspects of design and operation and why they are important.

- To discuss computer modeling (hydraulic and water quality) and illustrate some of the benefits and pitfalls.
1.0 RURAL WATER SUPPLY PIPELINES: DESIGN AND CONSTRUCTION
Rural Water Supply Systems

- Typically rural water supply pipeline projects occur because farms are forced into water haul situations (i.e. costs to haul or treat wells or surface sources is cost prohibitive).
- Pipelines are low pressure (typically less than 100 psi) usually constructed with HDPE (high density polyethylene) or PVC pipe.
- Typical sizes on feeder mains from 1 to 6 inches, however, transmission lines may consist of increased sizes / different materials.
- Typical peak flow rates – 1.0 igpm per service with minimum pressures to service (small storage tank) 100 kPa or 14 psi.
- Water flows to a storage vessel with an air gap. Home system is plumbed from the tank. Two systems are isolated.
- Some of the pipelines we come across do not enforce use of cisterns – many individuals rely on pipeline pressure, direct feed – issues arise when high consumption.
Safety – typically backflow prevention, dual checkvalves, in some cases double checkvalves. Are they working?

Bacteriological Water Quality Monitoring – Often hard to get representative sample from pipeline. Typically infrequent.

Chlorine monitoring even harder to get a handle on as it decays dependent on residency, reactivity with pipeline wall, source water quality and other factors.

- Most often asked question – Where should we sample chlorine residuals on our pipeline?

Branched pipelines (NOT LOOPED)

- Cheaper? However, no secondary circulation.
- Impact both the hydraulics, and water quality.

Water Quality somewhat at the mercy of the supplier/source

- THM’s, Turbidity, starting chlorine residual
Branched Distribution Systems

65 km of HDPE with each branch approximately 20 km
Looped Distribution Systems

Notice the looped design observing municipal design standards.
Contrasting Looping Parameters

- If we compare looping parameters with the City of Regina...
  For residential development looped connections must occur no less than 200 - 400 metres (depending on development density and pipe size / purpose). Also single supply line (dead end length) should be no longer than 150 metres.
  - This is for many of the same reasons previously mentioned (hydraulic efficiency, redundancy, secondary circulation and water quality).

- In contrast, in rural systems, it is not uncommon to have branch lengths of several kilometres with only one service connection. Can have detrimental effect on water quality.
Hydraulic Design Requirements

- Designers must make sure that;
  - Design for Peak Flows
    - Need to demonstrate that under peak demand conditions, there is sufficient pressure and minimum flows
    - Overdesign / Oversize the Pipe to Accommodate Future Growth:
      - Account for peak flows (present with some potential for future development – 10%) with minimal head loss or pressure drop.

As a result, under normal operating conditions, the pipeline velocities are relatively slow with extended detention time in the lines.
  - Results in poor circulation, aged water and often deteriorated water quality.
  - Peak velocities in my model at the take off point were approximately 0.4 m/s. Typical flushing requires at least 1.0 m/s to scour the lines.
  - Particulates settle out in the line, then when an incident occurs, water break, sudden high flow, re-suspension of material and water quality complaints
Advantages of HDPE

- Flexible – can be coiled and can be reliably connected (heat fusion) in the field.
- Easy to install if line diameter 150mm or less and soil conditions favourable (limitations in rocky soils).
  - Plough the pipes in with the use of cat trains, and / or we can bore under sensitive areas and existing utilities.
- Smooth surface – relatively non-reactive with water and soils resulting in limited “roughening” of pipe surface and minimal chemical interaction with fluid.
Coiled HDPE Loaded onto Plough
Cat/Plough Tooth
Cat Train Ploughing Pipe
Pipe Joining/Thermal Fusion

- Pipe ends are trimmed, disinfected, heated, then pressed together.
- Fusion welds are stronger than the pipe.
HDPE Pipe Installation - Boring

- Boring tool used to:
  - Bring service into basement.
  - Bore under other utilities.
Typical capital costs to cover pre-design, design, construction (with Federal funding) perhaps in the $16,000 – $20,000 per service.

Water use charges to cover items such as Certified Operator, sampling and testing requirements, maintenance, repairs ...

Hopefully there is enough in this service charge to build a capital expense account to look after future costs including the need for chlorine booster stations (costs $12,000 (equipment alone) - $100,000) – “it is not a matter of if, but rather when chlorine booster stations are required”.

I think of the dozen or so pipelines I deal with I only know of 2 or 3 that have all their valves working! Why?
2.0 STUDIES ON DETERIORATING QUALITY
Completed a study in 2002 for Saskatchewan Association of Rural Water Pipelines (SARWP).

**Findings**

- As long as a free residual maintained, limited to no measurable biofilm development / no visible interior pipe degradation.
- Biofilm development very much impacted by water temperature (suggested that $15^\circ$C was a growth threshold).
- In preparing this presentation came across a study suggesting that DOC may be more of a factor than chlorine or temp in biofilm formation.
Recognizing the potential impact / relationship between water quality and hydraulics, Putz modeled the two systems using the US EPANET hydraulic program.

Interest was in “residence time” / water age. Gathered detailed water use data.

Putz found that typical “residence times” 170 to 300 hours however in some branches, during low demand periods, residence times ranged from 550 to 580 hours (23-24 days!)

- Can a residual be maintained for that period?? Reactions with other constituents, the pipe wall and diffusion?
- What is the likely outcome? Nil Chlorine residudals and Biofilm development.
- No disinfectant residual protection in the event of contamination

- Biofilms can develop independent of pipe surface / type.
- Biofilms can develop in very short periods of time.
- Biofilms can to some degree, self preserve or insulate from future free residual doses.
What’s the big deal with biofilms?

- Biofilms are microorganisms that attach themselves to the pipe wall. Reproduce to form a complex and dynamic micro-ecosystem of slime.
- Usually harmless Heterotrophic bacteria
- Slough off into the water
- Although water is disinfected it is not necessarily sterile!
- May harbour bacteria, viruses, protozoa, fungus
- Typically harmless organisms, may cause health problems to immuno-suppressed individuals.
- Can lead to taste and odour and colour issues
So why do we need to maintain chlorine residuals?

- Control Biofilms
- Control bacteriologic regrowth
  - Bacteria protected are partially damaged through treatment may regrow and reproduce
- Some correlation between chlorine residual and biofilm growth. Organic and nutrient content of water a factor.
- There is a relationship that systems that maintained higher chlorine residuals have less incidences of positive coliform samples than those that do not.
- Remember – that coliform testing is only an indicator organism!
- Multi Barrier Approach to Water Safety – key point is maintaining chlorine residuals in distribution system!
The EPANET hydraulic modeling program was not used for water quality modeling by Putz, however, it did provide Putz with valuable information regarding where to sample – vulnerable locations.

Others have suggested that even if the delivery of the water is good, that degradation can commonly occur in the home storage tank or cistern – and this in fact is the larger risk issue.

- PFRA suggest only two day average volume use sized holding tank / cistern size – for good reason.
- Subscribers should be provided information on proper cleaning disinfection practices for holding tanks and cisterns.
Some Limitations of the Putz Study

- Limited sample locations!

- This is not a fault of his study. There is only so much you can do with the monies you have – are provided.

- More work to be done in understanding water quality degradation in rural water pipelines.
A couple of reasonably good studies characterizing chlorine reactivity and diffusivity – sure that there is lots more out there;


Good case studies based on observed field data and observation of hydraulics.

We can do more here in Saskatchewan!
3.0 MODELING - GENERAL
What is a computer model? – A computer program used to simulate a process/operation in order to predict and gain insight into how that process/operation works or will work. Used to optimize how the system works.

Hydraulic models are developed from hydraulic equations (Hazen–Williams, Darcy–Weisbach). Required inputs include pipe lengths and diameters, friction factors, loss coefficients for fittings. In EPANET pipes are called links and the users are called nodes.

In the field of hydraulics, the models provide a quick method to optimize design (get the optimum pipeline routes, sizes, material types and pressures).

An interesting note is that recognizing the dependent nature of water quality and hydraulics / hydrology, many software firms/ groups that produce hydraulic models have integrated (to some degree) water quality routines / algorithms into their software.
Is Water Quality and Hydraulics Related?

- Quality and Quantity are related! YES!

- There often is no point talking about water quality without flow data. The flow / hydraulics and water quality in any system are linked!

- An understanding of how the delivery network operates is required if you truly want to get at the heart of water quality issues.
Again, a number of software packages out there to model water quality in distribution systems.

- There are lots of criteria / factors that go into the decision of making that choice (cost, ease of use, support, training)

Beware though - when you now ask a model to do both hydraulics and water quality – lots more assumptions, and you have a much greater probability of inaccuracy as the number of inputs / assumptions increase.

Lots of accurate field data over a long period of time, over varying operating conditions is ideal to calibrate your model to behave like the actual distribution system.
When completing a typical water quality study, what types of information are required?

Hydraulic Inputs / Assumptions:
- Supply pressures delivery (real pump output), pipe roughness, minor losses, water use (average and peak use, peaking factors and water demand patterns; daily, weekly, seasonally.

Water Quality Inputs / Assumptions:
- All of the above plus ...
- Chlorine, ammonia, temperature, DOC .... Reactivity with other chemicals, the pipe material / wall – chlorine reactions and diffusion.

 Quite a list folks!
Hydraulic Modeling can be a challenge in itself.

When we start adding on the additional challenges associated with water quality .... another bag of uncertainties - unknowns and assumptions, you may find yourself questioning the results of the exercise / analysis.

- You MUST have calibration data!
- Assumptions based on assumptions!

Don’t blindly trust the output of models without good calibration!
Example Software Packages

- **US EPA EPANET** – freeware from the US EPA
  - Free is the operative word! Good program and good technical documentation – proven! But not the easiest to get around.
  - In addition to the hydraulics, it is capable of modeling 1st order bulk decay reactions, wall reactions and water age.

- **WaterCAD / WaterGEMS** (Bentley Systems – formerly Haestad Methods).
  - This package is often specified and employed in many jurisdictions; clearly recognized in the marketplace however, not a particularly cheap tool! $$$$$
  - Capable of Water Quality Analysis: Bulk and Wall reactivity as well as diffusivity.

- **HYDROMANTIS** Water Disinfection Software with Network Analysis Capability
  - Note the coupling of the hydraulics with the water quality components. WTP application – real time ct calculations, THM formation.

- Others ... **PICCOLO** by Safege Consulting Engineers; **CHLORINE** – University of Cincinnati . more ....
With all those assumptions, you must be able to take that model or “bag of equations” and ensure your assumptions are correct. Only then will you be able to use your model as a good “predictor”.

- Need calibration data – real field data
- See previous list of assumptions
4.0 EPANET Model Application
There are lots of packages out there and each has it’s pros and cons. You decide what you want. I decided to use EPANET as it was readily available online. One negative aspect is that it was not the most user friendly.

This is a model of a rural water distribution system serving 48 users. Materials are PVC and HDPE and total pipeline length is around 50 km.

Source Water is City of Moose Jaw. Significant detention times in City Line – lack of chlorine residual!

Water quality complaints in the past! – No easy flushing capabilities!

The ever popular question – Can we add more subscribers?

Significant elevation difference 50 meters from City to end – that’s 70psi!

One pressure boosting station
Where to Start

- EPANET computer can be downloaded and installed for free online from Environmental Protection Agency. Not the most user friendly. A very basic manual is available as well.

- Obtained as-builts from PFRA. Scaled a background image from Google Earth to draw the network of pipes (Links) to the farms/acreages on it. Used as-builts for pipe diameters and elevations.

- Some of the “better” software packages can use topographic maps and automatically determine elevations.
Obtain average water consumption data from pipeline and apply at each subscriber (node) Seasonal Variation!

Insert a source/supply for the system located and anticipated operating pressures provided or calculated. In this case for simplicity I used a reservoir with the approximate pressure (head) supplied by the City. Can model varying heads based on time. e.g. City static pressure probably higher at night. Variations are endless! Need actual data to calibrate model!

Valves (isolating, pressure regulating, blow-outs) placed in model.

Fitting need to be assigned or added to the model that result in headloss (valves, tees etc.)

Estimate the friction coefficient for the pipe based on the material used in construction. May change with time based on corrosion/deterioration/tuberculation. E.g. C=140

Are any pumping facilities required? Pump (characteristic) curves. Obtained 3 pump curves and built a pump curve representative of the three pumps at the pump building.
Links (pipes) & Nodes (users)

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Combining Pump Curves
EPANET Pump Curve Editor
Pipeline Design Criteria

- Distribution design completed in accordance with peak flows as specified in PFRA’s and MoE design manual = 1.0 igpm. Minimum Velocity of 0.6 m/s – can be hard to achieve. Loadings are used to ensure that minimum pressures exceed 100 kPa.(14psi)

- From Putz and others, we know that actual water use is less – on average 0.2 to 0.3 igpm and that demands during an operating cycle have peaking factor equal approximately;
  - Peak Day / Ave Day = 2
  - Peak Hour / Average Day = 5.

- Seasonal Variation – are farmers spraying?
Water Use Pattern
Calibration

What is calibration?

Modifying input data so that model output reflects that of observed data.

Hydraulically – measured pressures and flows at locations compared to model.

Quality – Measured Chlorine Residuals at locations compared to model.

Adjust coefficients (friction, chlorine reactivity)

Ideally conduct a tracer study
Hydraulic Model Output

- What does the model output?
  - Pressures at each location
  - Flow and velocities within the pipe
  - Single point in time or over an extended period
  - Water Age

- What do we need this data for?
  - Addition of customers
  - Determine where flushing would be important
  - Determine where areas of low pressure might be occurring.
## Predicting Velocities

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Water Age Results
Design Parameters

- Designers have to make the pipes (relatively) big in order to reduce head losses / pressure drop which results in water with extended detention time in the distribution system.
  - 7 days is a long time for chlorine residual to be maintained!
  - What other processes are taking place in that 7 days? Disinfection by-products produced, bacteriological growth, biofilm growth

- The bigger the pipes, the more difficult it will be to create scour velocities in the line, and in order to clean / maintain!
  - Biofilms need “trimming” – 1-2 m/s velocities required
  - Be careful about opening flush valves and “assuming” that you get adequate scour velocities – it may not happen!
Predicted Pressure Data
The program will allow you to model constituents – i.e. chlorine. However, predicting reaction rates is difficult….Function of numerous factors.

Important to start with a good hydraulic model

A good article that discusses chlorine reaction rates is “Kinetics of Chlorine Decay” by John J. Vasconcelos. Available through AWWA

- Consumption of chlorine is influenced by:
  - Reaction with organic/inorganic chemicals in water
  - Reaction with biofilms
  - Reaction with corrosive materials
  - Reaction between bulk flow and pipe wall

- Bulk Reaction Coefficient – First Order Reaction - Chlorine Concentration effects reaction rate. Can be determined by Bottle Test. (negative value for decay)

- Wall reaction Coefficient - Zero Order or First Order (pipe material interaction) (negative value for decay)
Ran the program with the default chlorine decay coefficients, inserted a residual of 1.5 mg/l at the source and completed the calculations with the model.

- Created “contour lines of anticipated chlorine residuals
- NOTE: Not calibrated, default values used as inputs

THESE VALUES ARE NOT ACCURATE WITHOUT CALIBRATION

Then ran the model by adding a chlorine booster station at the pumphouse that added 1.0 mg/l.
Please remember, a primary objective of ANY modeling exercise is to take this bag of equations (software), place into it good baseline data and assumptions, and then ultimately use the model to \textit{PREDICT} outcomes to some desired degree of certainty.

However, even with good input / assumptions, how do you know if you in fact have a good predictor?

Without \textbf{CALIBRATION DATA} – actual field information, much of what we can call results can be ..... 
- “Highly variable and not a good predictor”
- We have all heard the saying “garbage in = garbage out”
- Perhaps un-calibrated models can be of some limited use as “indicators” \pm ??%

Unfortunately calibration data is often one of the more expensive / difficult bits of information to collect, and because of that, is often chopped from budgets. Its importance is often overlooked.
So without field data folks, the highly variable nature of some models can in fact lead you down the wrong path. Be careful. ...
5.0 MAINTENANCE AND WATER QUALITY
You must look at both water quality and hydraulics to understand the causes and effects of system failure in order to remedy / solve the problem.

- My definition of success .. delivery of a product in sufficient quantity and quality.

So just to get off the topic with all you out there, what are the primary causes of system failure?

- Operator error and infrastructure breakdown – split?
  - Broken Valves – How Far can I turn this valve! Inexperience. Gate Valves, Ball Valves, Curb Stops – each has their own little trick!
    - Valve exercising
    - How many pipelines have their valve locations and curb stop locations properly documented?
  - Poor quality installation and materials
    - Not spec’d properly when tendered/installed
    - Someone overseeing installation, reputable contractor

Diagnosing System Failures
what are the primary causes of system failure cont’d?

- Clear Bylaws (which are enforced) as to which contractors can work on your pipeline.
- Automatic Air Release – Can leak, if submerged can be source of contamination. More common on larger diameter lines. Maintenance!
- Backflow Protection Devices need to be checked, serviced, or replaced!
  - Best way to keep you from getting a Precautionary Drinking Water Advisory in the event of a system de-pressurization. Environment Officer will take this into consideration as he weighs the risks!
After we make sure that we have a good water quality and good residual coming into the system, and assuming that there are no system breakdowns, reduced water quality could be MAINTENANCE related!

Some items include:

- **Flushing** ...
  - However can you get the velocities between 1.0 – 2.0 m/s velocity necessary to stir up sediments, and give biofilms a “haircut” (strong relationships with velocities).

- Hydraulic models can confirm best method for flushing. Greatest velocities. Flushing may also reduce air pocket development in pipelines. (air = excessive head losses)

- **Swabbing / pigging** – more aggressive approach to line cleaning. Do you have the ability to do it? Annual maintenance program.

- **Capital Works** – chlorine boosting facilities – Can be expensive
Flushing is Key - All Season!

• Get rid of “aged” water at the end of lines and increase velocity to scour pipe
• When water quality issues arise, water can be flushed out. (Positive Bact’s, Stirred up sediment, Maintenance Activities)
• When is water quality a concern - Usually Winter!
Chlorine Boosting and Monitoring

- Increase chlorine to limit bacteriological re-growth
- Protection in the event of accidental introduced contamination - system de-pressurization
- Protection after opening up the pipe for repairs, water breaks, valve replacement.
- Protection if supply source has problems maintaining quality
- Continuous Monitoring
  - set up to automatically adjust chlorine based on what existing chlorine levels are.
  - Alarm in the event of low chlorine levels
  - Store data that can be downloaded to a laptop to provide regulators, subscribers and design engineers with detail on chlorine residuals.
  - Get away from trying to find volunteers or good locations to sample from.
- Still important to periodically check chlorine residuals at ends of system!
Is your Source or Supply the Cause of some of your water quality problems?

- Maybe you are just not getting that chlorine residual from the system supply pipe!
- Many Source/Suppliers do not guarantee quality!
6.0 SOME THINGS WE CAN DO NOW
I would encourage you to look closely at the hydraulics of your rural pipeline systems; to look at weak points and collect field information that could better be used to protect the subscribers.

If you are looking at expansion perhaps modelling would be a good idea to see how your system will behave.

- Once you have the model created it will always be there to try new scenario’s.

Collect information (water quality) AND water quantity!

- Not only chlorine residual or bacteria counts, but other parameters (DOC, turbidity, ammonia, temperature)
- HYDRAULIC DATA: Flow rates and pressures
7.0 CONCLUDING REMARKS AND QUESTIONS
Are there any Comments or Questions?

If you have any further thoughts / questions, please do not hesitate to contact:
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Thank you for your time and attention.